IN-37

1618

p. 21

NASA Technical Memorandum 103716

High Temperature NASP Engine Seal Development

Bruce M. Steinetz and Matthew E. Melis
Lewis Research Center
Cleveland, Ohio

and

Dirk Orletski and Mark G. Test
Pratt & Whitney
West Palm Beach, Florida

February 1991

NASA

HIGH TEMPERATURE NASP ENGINE SEAL DEVELOPMENT

Bruce M. Steinetz and Matthew E. Melis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Dirk Orletski and Mark Test
Pratt & Whitney
West Palm Beach, Florida 33410

Key to the development of advanced hypersonic engines such as those being considered for the National Aerospace Plane (NASP) is the development and evaluation of high-temperature, flexible seals that must seal the many feet of gaps between the articulating and stationary engine panels. This paper will review recent seal progress made at NASA Lewis in the areas of seal concept maturation, test rig development, and performance tests. A test fixture has been built at NASA capable of subjecting candidate 3 ft long seals to engine simulated temperatures (up to 1500 °F), pressures (up to 100 psi), and engine wall distortions (up to 0.15 in. in only 18 in. span). Leakage performance test results at high temperature will be presented for an innovative high temperature, flexible ceramic wafer seal.

Also described is a joint Pratt & Whitney/NASA planned test program to evaluate thermal performance of a braided rope seal under engine simulated heat flux rates (up to 400 Btu/ft^2 s), and supersonic flow conditions. These conditions are produced by subjecting the seal specimen to hydrogen-oxygen rocket exhaust that flows tangent to the specimen.

NASP VEHICLE POWERED BY TWO-DIMENSIONAL RAMJET-SCRAMJET ENGINES (U)

Key to the development of a single-stage Earth-to-orbit vehicle is an advanced propulsion system that must be integrally designed with the airframe as conceptually shown here. To maintain sufficiently high specific impulse and reach orbital velocity (Mach 25), a hydrogen-burning, hypersonic engine is being considered. Similar to modern-day, two-dimensional turbojet nozzles, movable panels are being considered for the hypersonic engine. The extremely hot, pressurized engine flow-path gases must be prevented from escaping past the movable panels. Therefore hinge seals are required between adjacent movable panels, and panel-edge seals are required along each side of the movable panels. The discussion herein concentrates on the edge seals, since the total panel-edge seal length is more than twice the panel-hinge seal length.

Seals are required that can prevent leakage of engine flowpath gases pressurized to 100 psi and at temperatures in excess of air-hydrogen combustion temperatures (>4400 °F) with minimal coolant. Complicating the sealing challenge further is the need for the panel-edge seals to seal against severely distorted engine sidewalls. The high chamber pressures and heating rates cause the weight-minimized engine sidewalls to deflect in some cases as much as 0.15 in., bowing the engine panels into compound curvature or spherical-like shapes. In order to minimize leakage the panel-edge seals must be sufficiently preloaded and compliant to seal against these engine wall curvatures.

2

NASP ENGINE PANEL SEALS (U)

NASA Lewis Research Center is developing advanced seal concepts and sealing technology for the NASP propulsion system. The majority of the development effort has been applied to maturing panel-edge seals that seal the many feet of sliding seal interfaces between the movable engine panels and stationary splitter walls. An example of the seals being developed is the ceramic wafer seal shown mounted in the movable nozzle panel, one of the many movable panels in the engine. The goal of the panel edge seals is to prevent hot engine flow path gases, flowing beneath the engine panels in the figure, from escaping through the seal systems and damaging engine panel support and articulation systems.

The objective of this paper is to summarize the recent accomplishments in the areas of seal concept maturation, room- and high-temperature seal performance evaluation, and seal leakage model formulation. Plans for a joint Pratt & Whitney/NASA Lewis program to evaluate seal performance under engine simulated heating rates and supersonic flow conditions will also be reviewed.

CERAMIC
WAFER
SEAL

HIGH
SPEED
FLOW

SEAL CONCEPTS UNDER DEVELOPMENT (U)

Two seal designs that show promise of meeting the demanding operating conditions of the NASP engine environment and sealing the gaps between the movable horizontal panels and the vertical splitter walls are the ceramic wafer seal and the braided ceramic rope seal. The ceramic wafer seal developed by NASA Lewis Research Center (ref. 1) is constructed of multiple ceramic wafers mounted in a closely mating horizontal channel along side the movable horizontal engine panel. The seal is preloaded against the engine splitter wall using an active preload approach such as a series of cooled pressurized metal bellows shown in the figure. The bellows push against a flexible metal backing plate that distributes the load to the wafers between the discrete circular bellows. The wafer seal conforms to engine splitter wall distortions by relative sliding between adjacent wafers. Leakage tests conducted at room- and high-temperatures at NASA Lewis Research Center have shown this design accommodates and seals both straight and simulated distorted walls as will be described later in this paper. Also, steady-state thermal-structural analysis have shown (refs. 2 and 3) that this seal can withstand the severe (1160 Btu/ft^2 s) heating rates of Mach 10 flight using minimal cooling resources.

The braided ceramic rope seal is fabricated using either two- or three-dimensional braid architectures. Braiding the seal from alumina-boria-silicate (Nextel) fibers allows the seal to operate up to 2300 °F. Tests have shown (ref. 4) that these ceramic fibers maintain both strength and flexibility to this temperature. Two approaches are being considered to preload this seal against the splitter wall. In high heat flux environments a pressurized coolant gas is flowed down the axis of the seal. Using this approach the gas both inflates the seal conforming it to the expected engine wall distortions and effectively cools the seal. In lower heat flux environments where the heat conduction into the surfaces surrounding the seal is sufficient, preload systems made of either the metal-bellows shown or of ceramic springs are being considered. The nested ceramic spring preloader developed by Boeing Advanced Systems (ref. 5) offers high temperature (2300 °F) operation with sufficient preload force and flexibility to accommodate engine wall distortions.

CERAMIC WAFER SEAL

BRAIDED CERAMIC ROPE SEAL

4
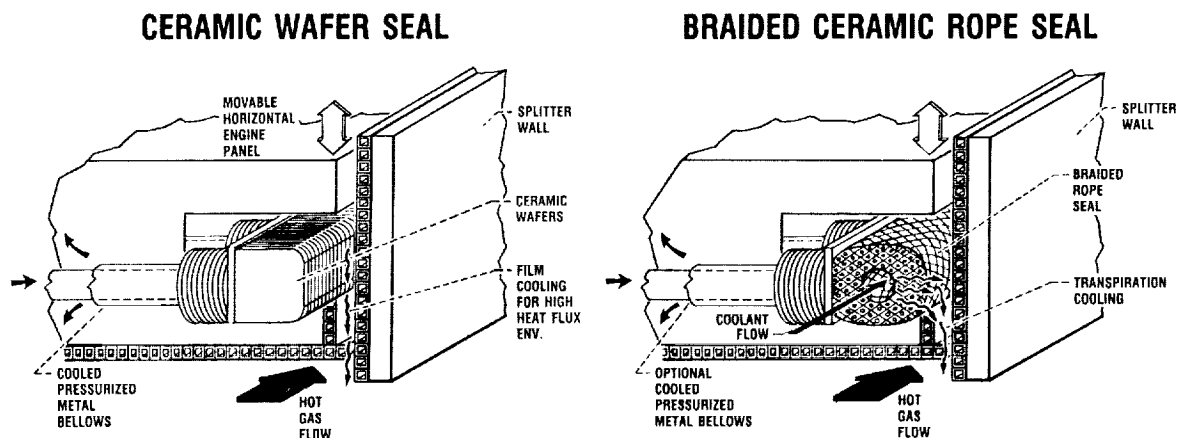
SCHEMATIC OF HIGH-TEMPERATURE PANEL-EDGE SEAL RIG (U)

A high temperature panel-edge seal test fixture has recently come on-line at NASA Lewis Research Center. The fixture can measure static seal leakage performance from room temperature up to 1500 °F, and air pressures up to 100 psi (ref. 6). Performance of the seals can be measured while sealing against flat or engine-simulated distorted walls by interchanging the front wall shown. These engine wall distortions can be as large as 0.150 in. in only an 18 in. span.

The Inconel test fixture is heated to the operating condition by high watt-density surface conduction heaters attached to the top and bottom of the rig. Simulated high temperature engine gas is supplied to the rig plenum by electric air heaters. Seal leakage is measured by flow meters upstream of these air heaters. The fixture is designed to evaluate seals 3 feet long, a typical engine panel length. The seal channel can be configured to test square, circular, or rectangular seals that are nominally 0.5 in. high. The sensitivity of leakage performance to lateral or axial loading can also be measured using specially designed high temperature lateral and axial bellows preload systems. Lateral load is applied using a series of high temperature, 0.5 in. diameter Inconel bellows located in the seal channel behind the seals. Load is transferred to the seal by the thin seal backing plate. Axial preload is applied through a hermetically sealed axial bellows/push rod loading system that can apply compressive or tensile loads to the seal over significant stroke lengths without leakage.

ADJUSTABLE LATERAL PRELOAD SYSTEM

3' TEST ZONE

AXIAL PRELOAD

AXIAL PRELOAD

HIGH WATT-DENSITY SURFACE HEATERS

HIGH-TEMPERATURE HEAD GASKET

INTERCHANGEABLE STRAIGHT AND DISTORTED WALLS

AXIAL PRELOAD

STATIC PRESSURE AND TEMPERATURE PROBES

CANDIDATE TEST SEAL

MULTIPLE PRELOAD BELLOWS

CERAMIC WAFER SEAL

0.150" DISTORTION 18" SPAN

0.5"

SECTION A-A

PRESSURIZED PLENUM (WITH MESH HEAT EXCHANGER)

1500 °F PRESSURIZED AIR (LEAKAGE METERED UPSTREAM)

CD-90-50896

5

NASP HIGH TEMPERATURE TEST FIXTURE (U)

The seal test fixture is shown in this photograph with a ceramic wafer seal installed (note the white horizontal stack of wafers mid-height in the rig). Testing of these linear seals requires special attention be paid to sealing their ends. Leakage around the ends of the seal is minimized using an approach in which over the last inch of both ends of the seal, the face of the fixture, the nose of the wafers, and the face of the front wall all meet in the same plane. Hence, in these two end sections there is no gap to seal. The air follows the path of least resistance and goes through the intended 36 in. center test zone.

Visible on the left and right ends of the fixture are the axial preloader systems mentioned earlier. These preloaders consist of a pneumatic actuator and a calibrated load cell applying axial loads to the seal through the hermetically sealed bellows push-rod assembly. Below the bench top are the electric air heaters and mass flow-meters. To minimize heat loss and expedite testing, low conductivity insulating board was carefully fit around the entire test fixture.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

6
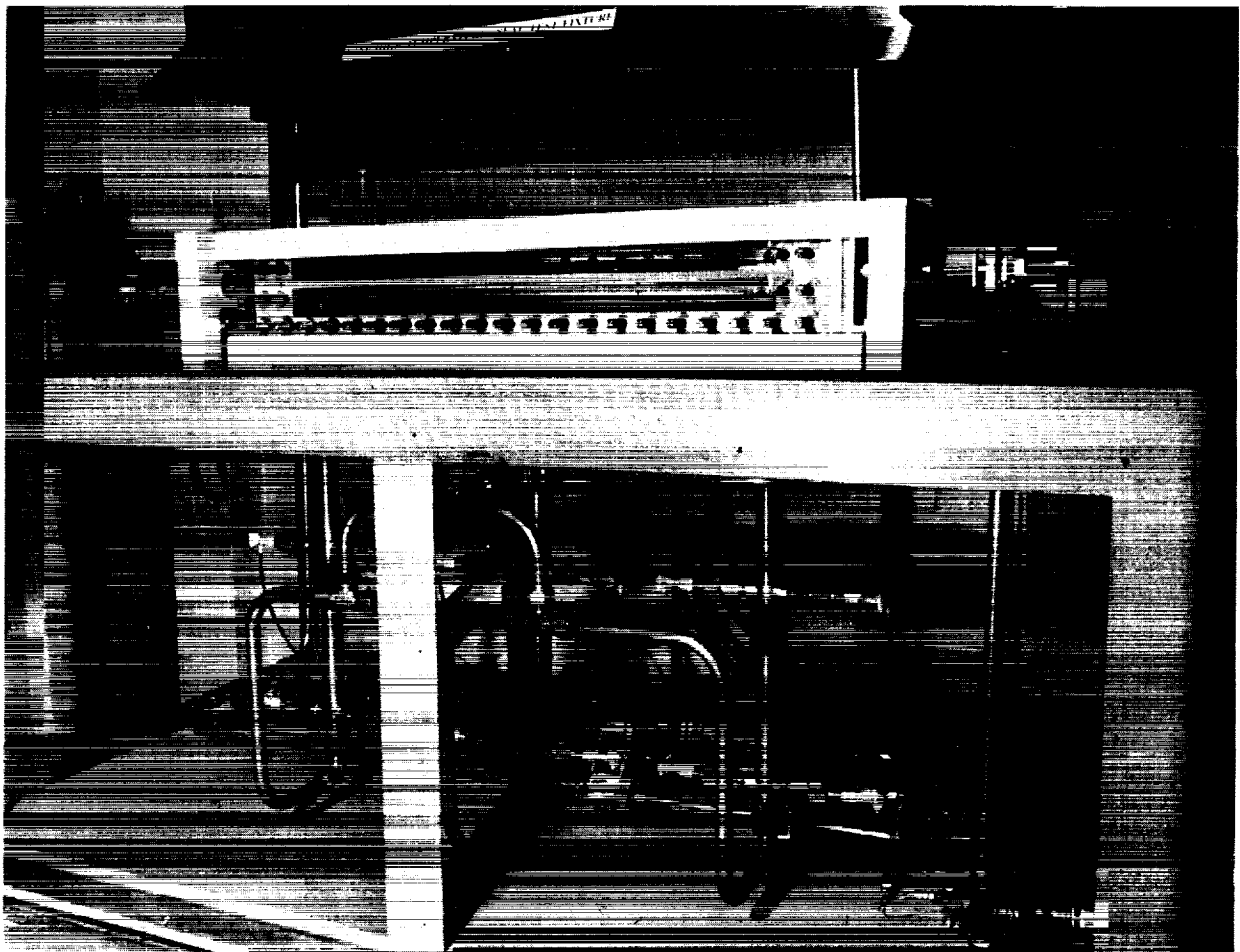
SEAL TEST FIXTURE THERMAL EXPANSION (U)

Design of this sizable seal test fixture for high temperature service required atten-
tion to be paid to issues not common to conventional design. Thermal growths, for
instance, were a particular design issue because of the large temperature rise and
large fixture size. The calculated thermal growth of the 40 in. fixture for over a
1400 °F temperature rise was 0.5 in. Ignoring thermal growths of this magnitude
often results in excessively high stresses that lead to unforgiving failures. The
thermal growth observed during testing was accommodated by slotted feet machined
into the rig base.

This thermal expansion also had to considered when designing the seal axial loading
systems. Many of the seal concepts to be tested in this fixture are made of ceramic
having a considerably lower coefficient of thermal expansion (CTE) than the Inconel
rig. To accommodate the differential expansion between the rig and the seals, long-
stroke hermetically-sealed axial preloaders are used to maintain axial loading on
the seal during operation. Differential thermal growth between the Inconel rig and
a 3 ft length of Al_2O_3 seal is 0.23 in.

CD-90-50888

7
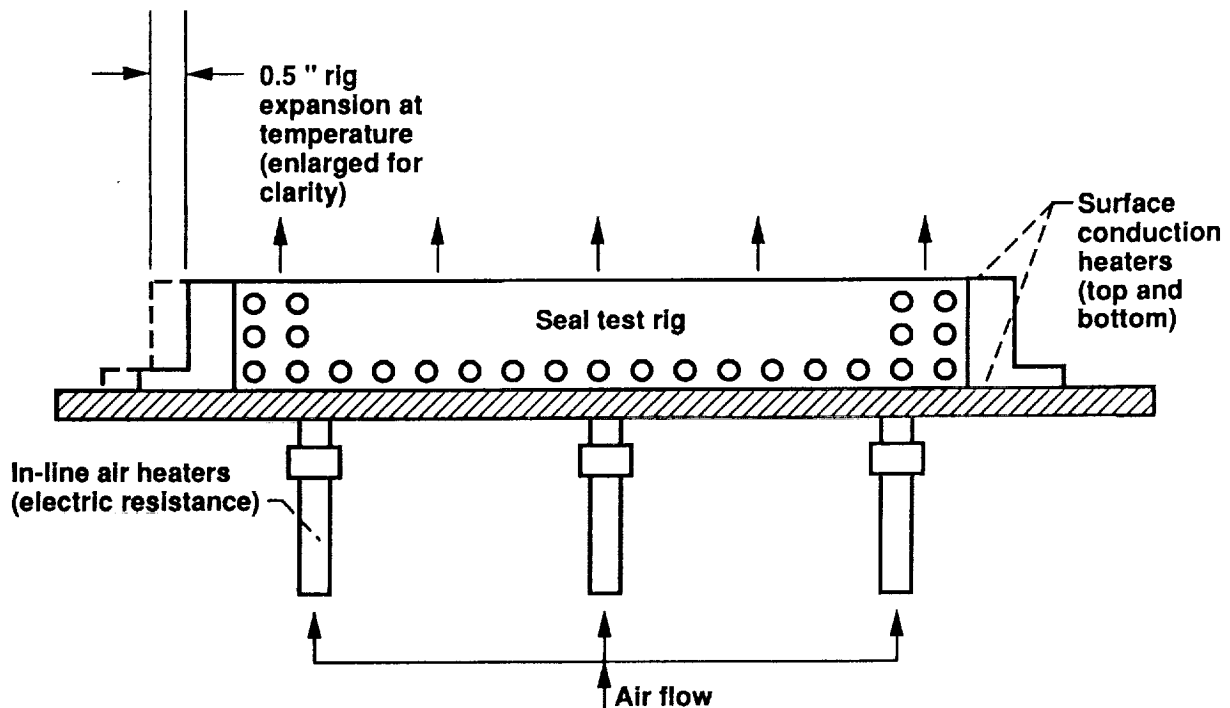
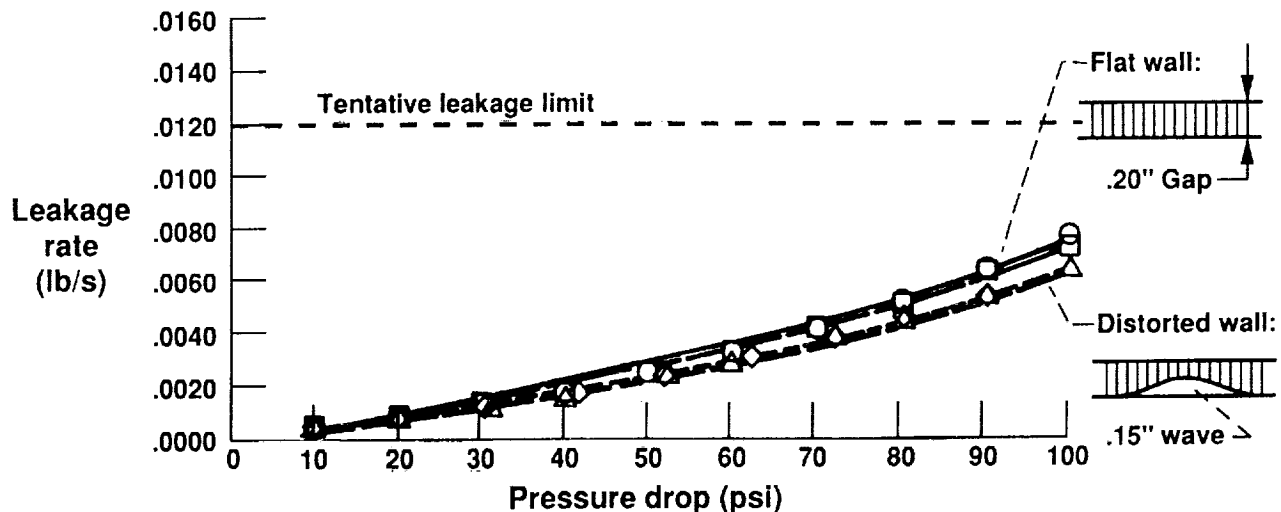## CERAMIC WAFER SEAL LEAKAGE PERFORMANCE (U)

The high temperature test fixture was used to assess the ceramic wafer seal leakage rates for pressures up to 100 psi and air temperatures up to 1350 °F (ref. 7). Air in the engine reaches this temperature 1 to 2 ft forward of the engine combustor for a Mach 8 (Q = 1500 psf) flight condition. The seal leakage rates were measured for two wall conditions including a flat wall condition and an engine simulated distorted wall condition. The leakage gap for the flat wall condition was 0.20 in. The leakage gap for the distorted wall condition varied sinusoidally from 0.050 in. in the center to the full 0.20 in. gap at each end. The total peak-to-peak distortion was 0.150 in. in only 18 in. of span.

The seal performed well in both cases with the leakage rates below the tentative leakage limit (ref. 1) for the full range of engine pressures and wall distortions. The measurements also demonstrate the repeatability of the seal leakage. The data for the flat wall condition represents a complete increasing-decreasing pressure cycle. The data for the distorted wall condition represents two complete pressure cycles. In all of the ceramic wafer seal tests reported herein the square wafers were 0.125 in. thick (ref. 1) and were made of aluminum-oxide ceramic. Axial load applied from both ends was 10 lbs. The lateral preload bellows were pressurized to 120 psi, which results in a contact pressure of ≈50 psi (e.g., the preload pressure is prorated by a factor of 2.5: the ratio of the seal area to the bellows area, see ref. 6) Prior to heating the rig and seal, the wafers were first preset to their preferred sealing position (e.g., in contact with the front wall and against the top of the seal channel) by the lateral preload pressure and engine pressure.


CD-90-50886

8

CERAMIC WAFER SEAL LEAKAGE MODEL (U)

Leakage models have been formulated for each class of seal under development. Leakage models are useful to seal designers for two important applications. A model allows designers to predict the small percentage of engine flow escaping past the seal as a function of pressure and temperature. These models can also be used to predict the flow rates of coolant gases past the seal in engine regions, such as the combustor, where a positive backside purge of inert gas is used to cool the seals and prevent leakage of potentially explosive mixtures of hydrogen and oxygen.

The ceramic wafer seal leakage model (see also ref. 7) is based on the theory of externally pressurized gas film bearings where the clearances are small and the flow is laminar (e.g., the Reynolds number is <500). In this model the mass flow is proportional to: the difference in the squares of the upstream and downstream pressures; the cube of the effective surface leakage gap h_i; and the seal length L. The leakage flow is inversely proportional to: the gas viscosity; the gas constant; the gas temperature; and the wafer dimension in contact with the adjacent surface.

Three leakage paths are identified for the wafer seal including: the gap between the wafers and the adjacent splitter wall; the gap between the low pressure (e.g., top surface) of the wafers and the seal channel; and the small gaps that form between the wafers caused by differential axial expansion. Small gaps (≈ 0.001 in.) open between wafers because the wafers made of ceramic do not grow in the axial direction as much as the channel (simulating the movable engine panel), made here of Inconel metal. The gap size is calculated by: the product of the difference in the wafer and rig CTEs; the seal length, and the temperature rise; divided by the number of wafer interfaces which is one less that the number of wafers used.
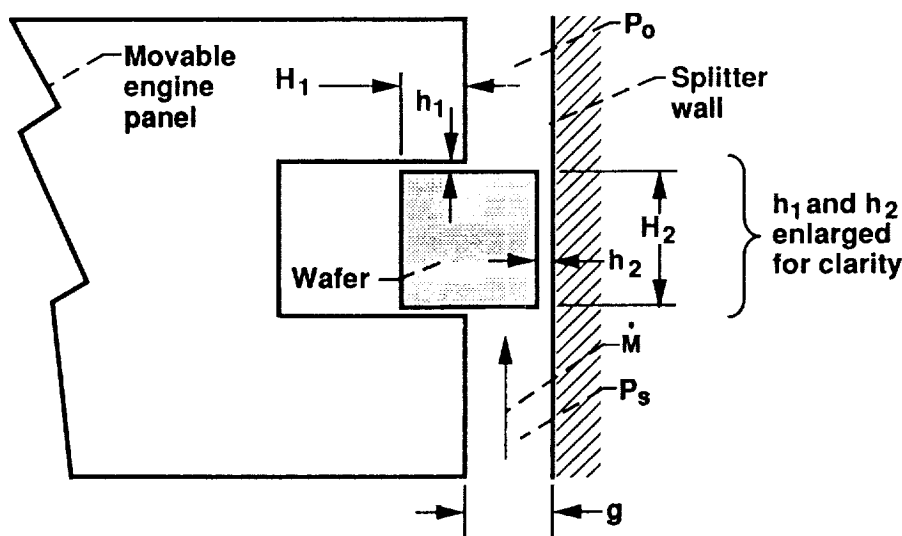
Where:
$\dot{M}$ = Seal leakage rate
h_1, h_2 = Eff surface leakage gap
L = Seal length

μ (T) = Power law viscosity

$h_s = \dfrac{\Delta CTE \times L \times \Delta T}{N}$ = small inter-wafer gap

N = No. of Interfaces

$$\dot{M} = \frac{(P_s^2 - P_o^2)}{24\,\mu\,R\,\,T}\left(\underbrace{\frac{Lh_1^3}{H_1} + \frac{Lh_2^3}{H_2}}_{\text{Parasitic leakage around wafers}} + \underbrace{\frac{Ngh_s^3}{H_2}}_{\text{CTE mismatch Induced leakage}}\right)$$

9

CERAMIC WAFER SEAL LEAKAGE TEMPERATURE DEPENDENCE (U)

Leakage data for the ceramic wafer seal are plotted as a function of temperature for a fixed pressure differential of 40 psi, sealing against the flat wall. The seal leakage rates are significantly below the tentative leakage limit for the full range of temperatures measured. The seal leakage measured in mass flow actually decreases with increasing temperature for temperatures up to just under 1000 °F. Following this temperature a slight increase in leakage rated is observed.

The decrease in mass flow is attributed to the fact that gas viscosity increases with temperature making it more difficult for the gas to pass through tiny gaps. At a certain temperature however the effect of increased mass flowing through the small inter-wafer gaps, caused by the differential axial growth between the wafers and the engine panel, begins to overtake the effect of reduced flow caused by increasing gas viscosity.

The leakage rates predicted using the previously described model are also plotted in the figure. The predicted variation of leakage with temperature closely follows the measured data. The room temperature measured leakage rate is used to calculate the effective surface leakage gaps h_1 and h_2 for the model. Using this procedure also "calibrates" the model to account for the installed conditions of the seal. The measured leakage being slightly higher than the predicted values can be caused by several factors, including: a small amount of end leakage around the wafers not accounted for in the model; and thermally-induced, nonuniform changes in the size and shape of the film heights (h_i). Since the flow responds to changes in gap height cubed one can see why thermally-induced changes in contact condition can lead to variations in leakage.
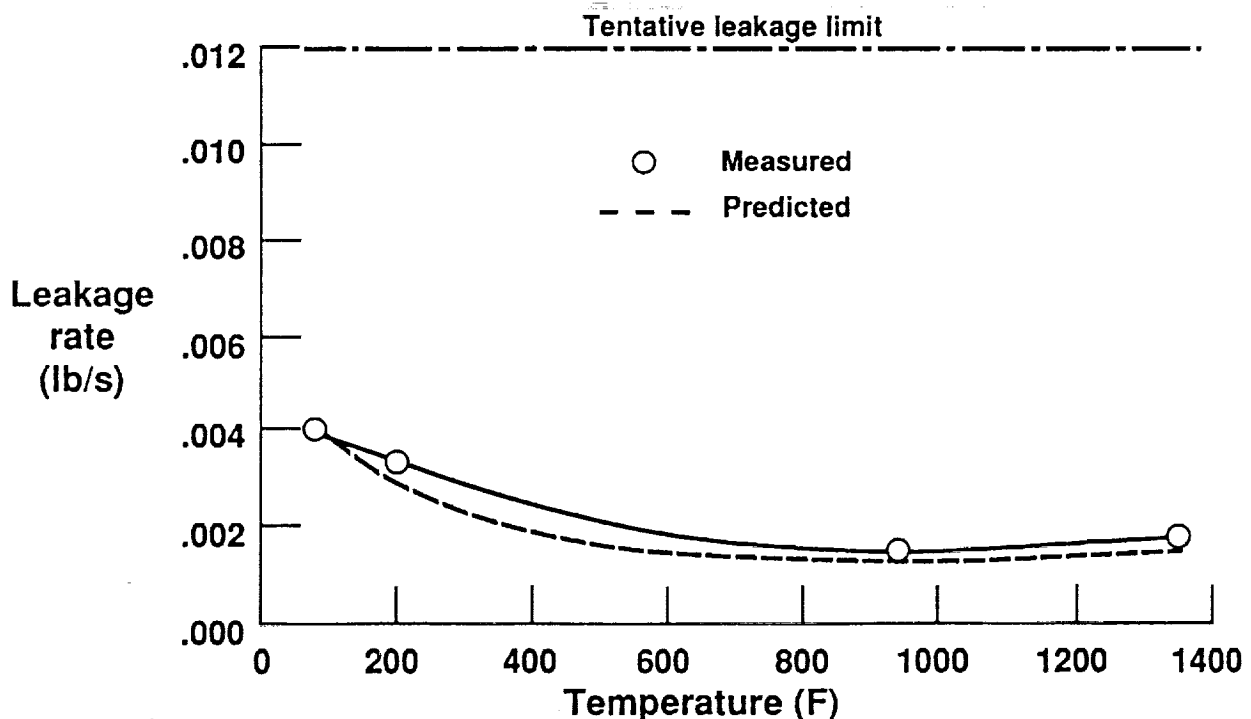
CD-90-50890

BRAIDED ROPE SEAL TECHNOLOGY DEVELOPMENT (U)

During the seal concept development phase of the program the combined flexibility and high temperature capabilities of alumina-boria-silicate (e.g. Nextel) fibers showed significant promise for NASP seals presuming low leakage, durable seal structures could be made from them. Drexel University is under contract with NASA Lewis to develop design methods and processing approaches to optimize braided rope seal performance. The goals of this program are to develop an integrated design framework linking seal performance measured in terms of leakage and flexibility to key braiding parameters including: fiber and yarn diameters; fiber volume fractions; and braid architectures, amongst others. Two and three dimensional braid architectures with high packing densities were selected for their anticipated low permeability. Emphasis was placed on low permeability designs in order to meet the stringent low leakage design criteria.

A matrix of seals 0.5 in. in diameter by 14 in. long were fabricated and leak tested (using both air and helium gas) in a specially designed room temperature seal test fixture. The resulting data is being used to rank the braided seal performance relative to the tentative leakage limit and to validate braided rope seal leakage models being developed in parallel.

Objective: Develop design methods and processing approaches to optimize braided rope seal performance

Approach:
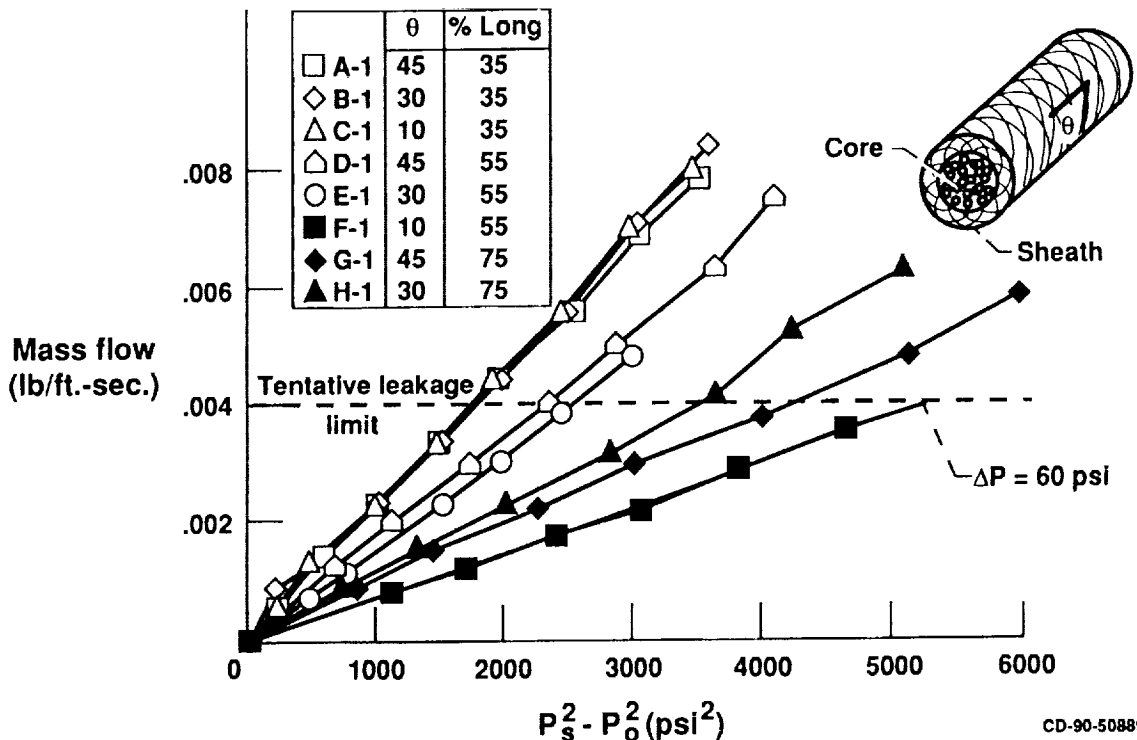1. Develop integrated design framework linking seal performance (eg. leakage, flexibility, etc.) to key braiding parameters

2. Select fiber architectures to meet seal design criteria

3. Fabricate prototype seals for evaluation

4. Verify design methods, leakage models, and processing approaches through installed tests

CD-90-50894

11

TWO-DIMENSIONAL BRAIDED ROPE SEAL LEAKAGE PERFORMANCE (U)

A family of eight two-dimensional braided seals were produced and leak tested for engine pressure differentials to just over 60 psi. These seals consisted of a core made of uniaxial fibers with a two-dimensional braided sheath or cover to give the seal structural integrity. The room temperature air data shown here are for three percentages (35, 55, 75 percent) of uniaxial or longitudinal fibers and three braiding angles (10°, 30°, 45°). To minimize costs E-glass yarns having nominally the same denier (812 denier) and fiber diameter (10 μm) as Nextel yarns were used. The only seal in this 3 x 3 matrix not tested was a seal with a 75 percent longitudinal core and a 10° braid angle which had inadequate structural integrity. Seal specimens were tested at lateral preloads of 80 and 130 psi. The data shown are for an 80 psi lateral preload pressure applied by a linear diaphragm along the backside of the seal.

The general data trends indicate that relatively low leakage can be obtained using high percentages of longitudinal fibers, low to moderate braiding angles, small diameter yarns, the smallest diameter fibers possible, and firm lateral preloads. The interaction between surface braid angle and percent longitudinal core is still being investigated. Acceptable braided rope seal leakage rates, as compared to the tentative leakage limit, have been obtained for pressure differentials up to 60 psi and 80 psi for lateral preload pressures of 80 and 130 psi, respectively. In all test cases presented the seal downstream pressure is atmospheric.

	θ	% Long
☐ A-1	45	35
◇ B-1	30	35
△ C-1	10	35
⬠ D-1	45	55
○ E-1	30	55
■ F-1	10	55
◆ G-1	45	75
▲ H-1	30	75

Mass flow (lb/ft.-sec.)

Tentative leakage limit

Core — Sheath

$\Delta P = 60$ psi

$P_s^2 - P_o^2 (psi^2)$

CD-90-50889

12

BRAIDED ROPE SEAL LEAKAGE MODEL (U)

A leakage model for the two-dimensional braided rope seal structures has been formulated. The model treats the seal structure as a system of flow resistances analogous to a series of resistors in an electrical network. For the purposes of this model development, resistance is defined as the ratio of the difference in the squares of the upstream and downstream pressure (e.g., the flow potential) to the mass flow per unit seal length (e.g., the current). This approach allows the fundamental in-homogeneity of the seal's core and sheath to be characterized. These resistances are added as in an electrical network (e.g., resistances in series add; resistances in parallel add by their inverses) to form an equivalent seal resistance. Resistances of the fiber bundles are calculated using the Kozeny-Carmen relation where the characteristic size dimension is a scaled fiber diameter (e.g., 0.75 D_f; ref. 8), based on experimental observations. Each of these resistances are made up of the product of four terms: the first term captures the properties of the gas (e.g., viscosity, gas constant, temperature and molecular weight); the second term is a ratio of the length-to-thickness of that piece of seal; a term containing the reciprocal of $(0.75 \ D_f)^2$; and a term containing a porosity factor (e.g., $(1-\epsilon_s)^2/\epsilon_s^3$). Details of this model development are contained in reference 8.

As shown in the figure, the sheath is broken down into four resistances depending if the sheath is parallel or perpendicular to the flow direction. The resistance of the core is modelled by its own resistance that is markedly different from those of the sheath. Surface flows between the nose of the seal and the adjacent splitter wall and between the top of the seal and the adjacent channel surface are also factored into the model. Adding these seven resistances together according to their electrical analog characterizes the seal for the leakage predictions.
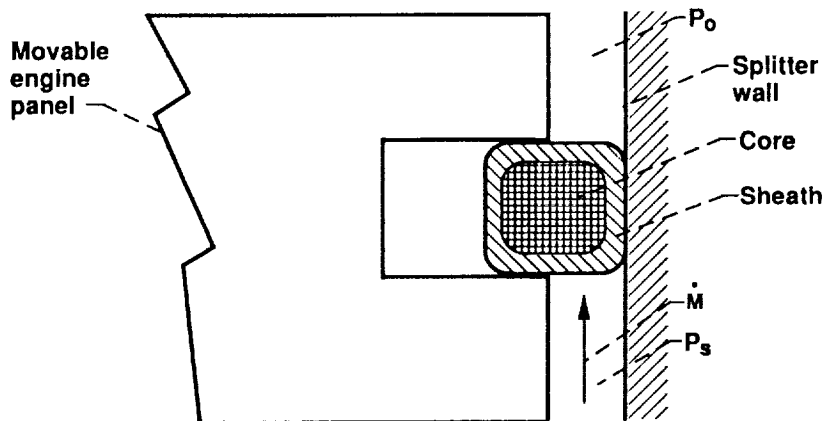
$$\frac{\dot{M}}{L} = \frac{P_s^2 - P_o^2}{R}; \quad \frac{1}{R} = \left(\frac{\text{Eff Seal}}{\text{Resistance}}\right)^{-1} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5 + R_6 + R_7}$$

Where:

$\dot{M}/L$ = Seal leakage per unit length

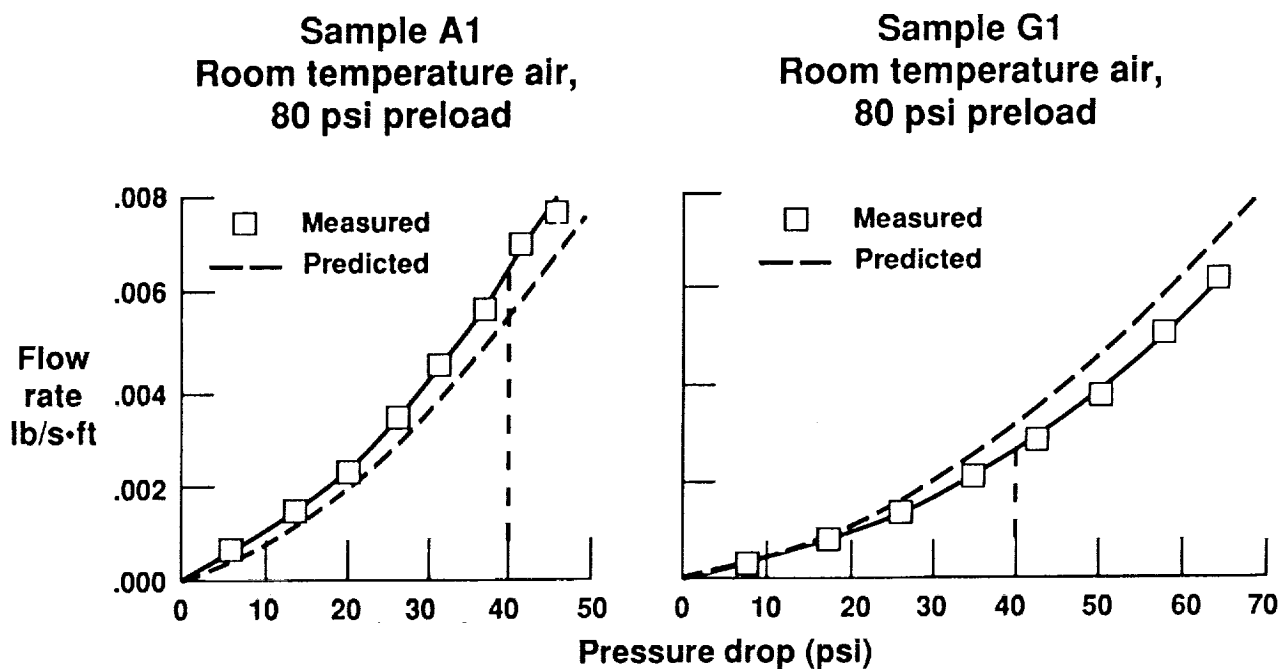R_1, R_2 = Resistance to flow behind and in-front of seal

R_3, R_4 = Sheath resistance (eg parallel to flow direction)

R_5, R_7 = Sheath resistance (eg perpendicular to flow direction, upstream and downstream)

R_6 = Core resistance

CD-90-50887

13

BRAIDED ROPE SEAL LEAKAGE:
COMPARISON OF MEASURED AND PREDICTED LEAKAGE RATES (U)

Measured leakage rates for two different seal architectures (denoted A1 and G1) are plotted here along with the predictions made using the previously described leakage model. The leakage rates are for air using an 80 psi lateral seal preload. The predicted leakage rates agree favorably to the measurements for both of these architectures, even though the absolute leakage rates of the two specimens differ by a factor of almost 2.5. The discrepancy noted between the measured and predicted values is generally less than 20 percent for seal A1, and less than 30 percent for seal G1. The sources of these discrepancies can include: some variability in installed and ideal fiber packing densities; data scatter; and some small unavoidable end leakage. These predictions are substantially closer to the measured values than those obtained with the unmodified, homogeneous-porous-media predictions of the Kozeny-Carmen relations which underestimate leakage rates by more than an order of magnitude. Ongoing model refinements are aimed at minimizing the noted discrepancies and accounting for the effects of seal preload on seal permeability.
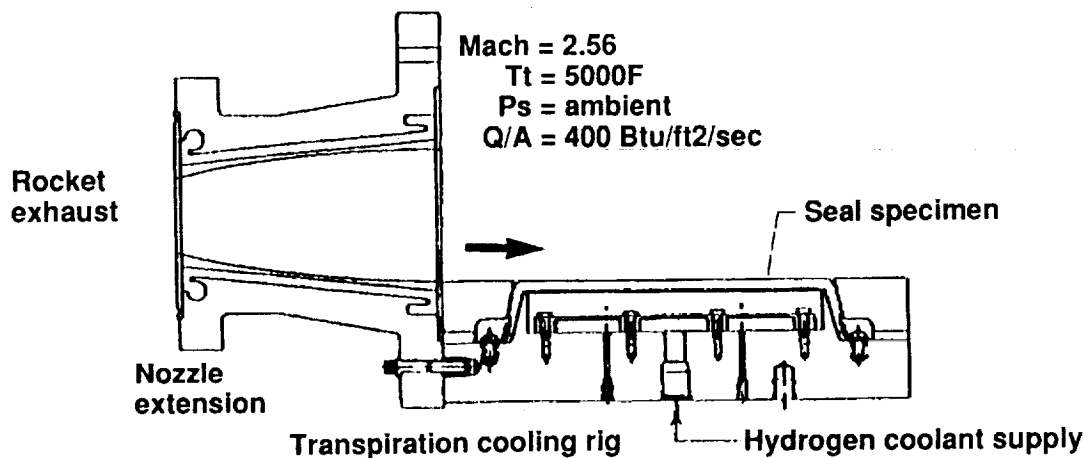
Sample A1
Room temperature air,
80 psi preload

Sample G1
Room temperature air,
80 psi preload

CD-90-50891

14

The heating rates within the NASP engine are severe ranging up to 1160 Btu/ft^2 s for a Mach 10 flight condition (ref. 3). Compounding the seal challenge is the erosive supersonic flow condition present while operating in the SCRAMJET mode. To assess the survivability of the braided rope seal design, P&W and NASA Lewis Research Center have established a cooperative project to test braided rope seals in the exhaust of an air-hydrogen rocket at NASA. The rocket exhaust is supersonically expanded in the nozzle extension shown. The hot (5000 °F total temperature) gas flows over a 6 in. length of the braided seal held in a heat-sink copper test fixture. Analyses indicate the seal will be subjected to a heat flux of 400 Btu/ft^2 s. No enclosure exists around the seal fixture so surrounding pressure is ambient.

In addition to assessing seal survivability, the tests will also be used to define transpiration cooling effectiveness for various coolant supply conditions. Either nitrogen gas or liquid nitrogen chilled hydrogen coolant gas will be transpired though the braid. Temperature and coolant flow rate measurements made will be used to determine the seal coolant effectiveness.

Mach = 2.56
Tt = 5000F
Ps = ambient
Q/A = 400 Btu/ft2/sec

Rocket exhaust

Seal specimen

Nozzle extension

Transpiration cooling rig   Hydrogen coolant supply

Goals:

• Evaluate seal survivability in highly erosive, supersonic flow field

• Define cooling effectiveness for various coolant supply conditions

Status: Fixture hardware: Complete
        Nozzle extension: in Process
        Begin Test: First Quarter, 1991

CD-90-50892

TRANSPIRATION FIXTURE HARDWARE (U)

Shown here is the copper transpiration fixture test hardware. Part of the braided rope specimen (white in the figure) is exposed to the hot rocket exhaust gas. Bolting the seal plate (foreground) to the shim and base plates firmly captures and clamps the seal specimen in-place. To limit the flow through high permeability braids a regimesh plate is mounted in the base plate. The fixture hardware shown is complete.

The nozzle extension for the existing rocket is in-process. Plans call for all hardware to be complete and tests to commence in the first quarter of 1991.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

ROCKET TEST FACILITY (U)

The rocket test facility to be used for the transpiration seal tests is operational and is shown here during a hot test of a candidate engine cowl-lip. The hydrogen-oxygen rocket fires for 3 to 4 sec. Using the supersonic nozzle extension total temperatures up to 5000 °F and stagnation heat fluxes up to 2500 Btu/ft^2 s are possible. Complete details of the test capabilities of the facility are found in reference 9.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

17
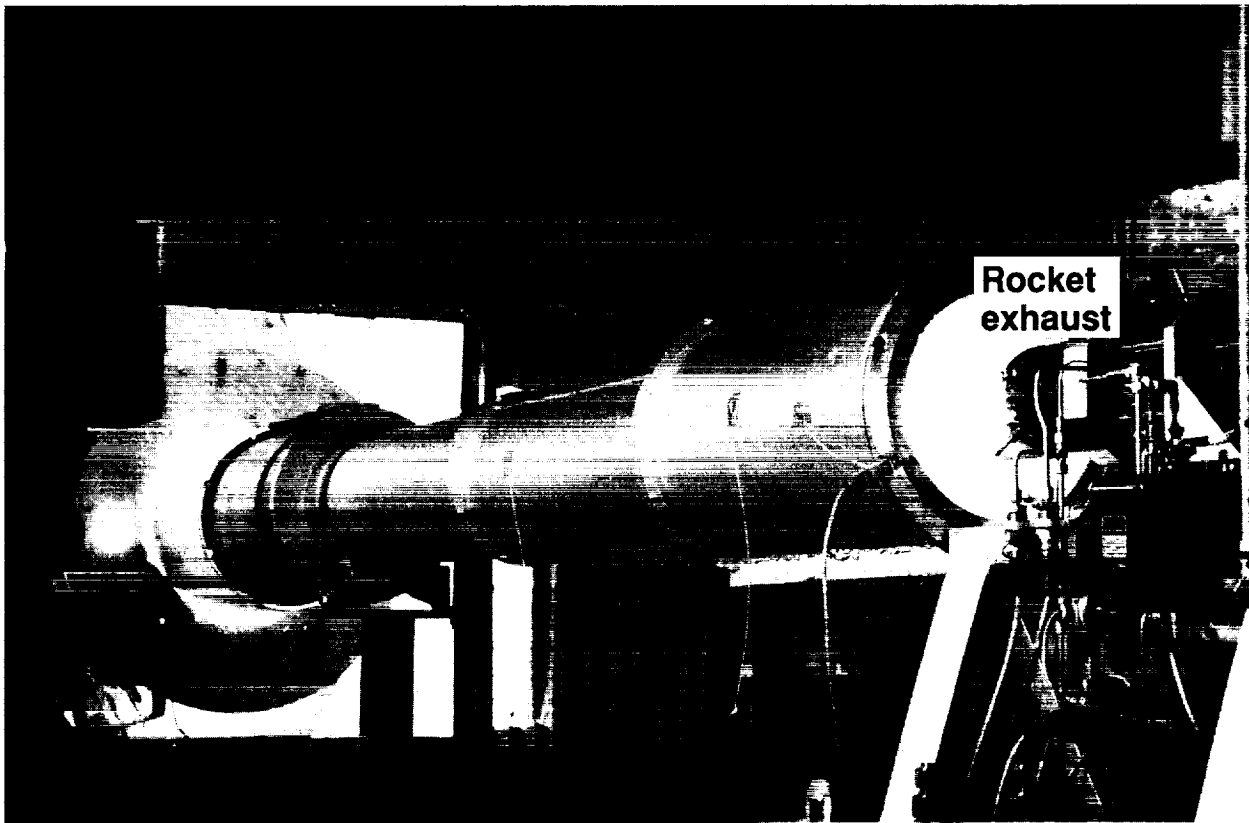
SUMMARY AND CONCLUSIONS (U)

Significant progress has been made in maturing and assessing the performance of two classes of NASP engine seals. The ceramic wafer seal has proven effective in minimizing leakage of hot simulated engine gases from room temperature up to 1350 °F, and for the full range of 0 to 100 psi engine pressure differential. The ceramic wafer seal meets the tentative leakage limit for all combinations of temperature, pressure, and adjacent wall conditions examined sealing both flat and engine simulated distorted walls. The wafer seal leakage rates were assessed using a static seal test fixture capable of 1500 °F operation installed at NASA Lewis Research Center. This test fixture will play an important role in evaluating candidate seal performances as the NASP project progresses toward the X-30 research vehicle.

Key braiding parameters have been identified for minimizing seal permeability and leakage rates for two-dimensional braided rope seals. Low leakage can be obtained by using: a relatively high percentage of longitudinal fibers; low to moderate braiding angles; small diameter fibers bundled in low denier yarns; and firm lateral preload. A seal structure made using these design specifications met the tentative leakage limit at room temperature for engine pressure differentials of 60 and 80 psi for lateral preloads of 80 and 130 psi, respectively. Three feet long seals made to these specifications using Nextel fibers are scheduled for test in the high temperature test fixture at NASA Lewis.

Leakage models for each of the ceramic wafers and braided rope seals have been formulated. These models useful in predicting seal leakage rates for the broad range of engine temperatures and pressures are being validated using experimental data obtained from the high temperature test fixture.

A cooperative P&W/NASA Lewis program has been established to assess braided rope seal survivability and cooling effectiveness in the supersonic, high heat flux environment typical of the NASP engine. Candidate braided rope seals will be subjected to a 400 Btu/ft^2 s heat flux in a Mach 2.56 rocket exhaust flow.

- **Ceramic wafer seal performance assessed at temperatures up to 1350 F and to pressures up to 100 psi.**
  Seal meets the tentative leakage limit for both flat and engine simulated distorted wall conditions.

- **High temperature seal test fixture is operational at NASA Lewis.**
  Unique test capability to assess candidate seal seal leakage rates as project progresses toward X-30.

- **Key braided rope seal parameters limiting leakage identified.**
  Low leakage braided seals tested that meet tentative leakage limit for pressures up to 60 psi.

- **Leakage models for each class of seal developed. Tests underway to validate/refine over full engine operating conditions.**

- **Planned PW/NASA hot gas seal tests to assess seal survivability and define coolant effectiveness at 400 Btu/sqft s heating rates.**

REFERENCES

1. Steinetz, B.M.; DellaCorte, C.; and Sirocky, P.J.: On the Development of Hypersonic Engine Seals. NASA TP-2854, 1988.

2. Steinetz, B.M.; DellaCorte, C.; and Tong, M.: Seal Concept and Material Performance Evaluation for the NASP Engine. NASA CP-7045, Vol. VI, Structures, 1989, pp. 39-58.

3. Tong, M.; and Steinetz, B.M.: Thermal and Structural Assessments of a Ceramic Wafer Seal in a Hypersonic Engine. NASA TM-103651, 1991.

4. Sawko, P.W.; and Tran, H.K.: Strength and Flexibility Properties of Advanced Ceramic Fabrics. SAMPE Q., vol. 17, no. 1, Oct. 1985, pp. 7-13.

5. Dursch, H.W., et al.: National Aerospace Plane (NASP) Airframe Technology Option Five: Sealing Concepts, Final report. Air Force Contract No. F33657-86-C-0061, Boeing Advanced Systems, July 21, 1989.

6. Steinetz, B.M.: A Test Fixture for Measuring High-Temperature Hypersonic Engine Seal Performance. NASA TM-103658, 1991.

7. Steinetz, B.M.: High Temperature Performance Evaluation of a Hypersonic Engine Ceramic Wafer Seal. NASA TM-103737, Feb. 1991.

8. Mutharasan, R.; Steinetz, B.M.; Tao, X.; and Ko, F.: Development of Braided Rope Seals for Hypersonic Engine Applications, Part II: Flow Modelling. To be published as NASA TM. Also accepted for presentation at the 27th AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Sacramento, CA, June 1991.

9. Melis, M.E.; Gladden, H.J.; Schubert, J.; Westfall, L.; and Trimarchi, P.: A Unique Interdisciplinary Research Effort to Support Cowl Lip Technology Development for Hypersonic Applications. NASA TP-2876, 1989.

1. Report No. NASA TM–103716	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle High Temperature NASP Engine Seal Development		5. Report Date February 1991
		6. Performing Organization Code

7. Author(s) Bruce M. Steinetz, Matthew E. Melis, Dirk Orletski, and Mark G. Test		8. Performing Organization Report No. E–5949
		10. Work Unit No. 505–63–1B
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135–3191		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546–0001		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

16. Abstract

Key to the development of advanced hypersonic engines such as those being considered for the National Aerospace Plane (NASP) is the development and evaluation of high-temperature, flexible seals that must seal the many feet of gaps between the articulating and stationary engine panels. This paper will review recent seal progress made at NASA Lewis in the areas of seal concept maturation, test rig development, and performance tests. A test fixture has been built at NASA capable of subjecting candidate 3 ft long seals to engine simulated temperatures (up to 1500 °F), pressures (up to 100 psi), and engine wall distortions (up to 0.15 in only 18 in. span). Leakage performance test results at high temperature will be presented for an innovative high temperature, flexible ceramic wafer seal. Also described is a joint Pratt & Whitney/NASA planned test program to evaluate thermal performance of a braided rope seal under engine simulated heat flux rates (up to 400 Btu/ft^2 s), and supersonic flow conditions. These conditions are produced by subjecting the seal specimen to hydrogen-oxygen rocket exhaust that flows tangent to the specimen.

17. Key Words (Suggested by Author(s)) Seals Hypersonic engines Design Test fixtures	18. Distribution Statement Unclassified – Unlimited Subject Category 37	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 20	22. Price* A03